Chapter 4
Energy Management of Complex Buildings as a System

Energy management of complex buildings is a set of mutually connected energy branches (energy processes and installations) the aim of which is the production, transport, and distribution of energy carriers to consumers (e.g. office rooms and garages). Due to these connections, the energy management treated as a whole is characterized by features not displayed by particular energy branches considered separately [5]. Therefore, energy management of complex buildings can be considered as a system from the viewpoint of the oldest definition of system formulated by Aristotle [7].

Typical complex buildings are, among others, airports, hospitals, office buildings, sports and recreation buildings, and shopping centers. The centralized supply of complex buildings with final energy carriers (electricity and heat) is realized by the domestic electro-energy system and district heating systems. Centralized supply with final energy carriers is more and more often replaced by modern distributed energy systems. The application of distributed energy systems reduces losses due to the transmission and distribution of energy to consumers. Decentralized supply of heat and electricity is more often realized by small-scale cogeneration systems, which may be equipped with piston engines, microturbines, Stirling engines, and fuel cells. Small-scale cogeneration systems may be connected to cooling installations realizing the "trigeneration" technology (BCHP-building, cooling, heating, and power). In modern distributed energy systems, the application of renewable energy sources is increasing, mainly by solar energy (solar collectors and solar photovoltaics). Ground-sourced heat pumps are also applied.

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4.1 System Approach to Energy Analysis of Complex Buildings

Nowadays, complex buildings are characterized by a large variety of energy requirements, which involves a complexity of energy management. The term “complex buildings” denotes one building or a set of buildings, the energy management of which is complicated (e.g. supermarkets, airports, and recreation centers).

Final energy carriers (electricity and heat) are used in complex buildings to provide a variety of services, such as lighting, space heating, hot tap water production, space cooling, refrigeration, dehumidification, and electricity for internal equipment. The production and consumption of energy carriers in complex buildings take place within a network of interconnected processes. In complex buildings, the connections between the production and consumption of energy carriers means that global energy management is more than the sum of energy processes considered separately. This last sentence, if not applied merely to energy, is the oldest definition of the system reaching back to Aristotle. Thus, the energy management of complex buildings is a system defined as a set of energy installations, devices and interconnections between them, as well as external connections with the environment. Due to these interconnections, energy management treated as a whole is characterized by features not displayed by its parts (the respective energy branches such as, for instance, hot tap water or a cooling agent).

Energy management of complex buildings considered as a large energy system belongs to continuously developing artificial hierarchical systems, in which people are organically connected with the controlling and controlled parts of the system. The energy subsystem of complex buildings displays features of both technical (cybernetic) and economic systems. The technical character of the energy subsystem results from the material and energy connections between the elements [13]. The activity of people in the controlling and controlled elements of the system determines its economic character.

A characteristic feature of the energy subsystem as an organized system is its hierarchical structure. This property consists in the fact that the respective elements of the energy subsystem (the respective branches producing energy carriers) are subsystems of a lower order, and the energy management as a whole is considered to be a system on a higher level. The energy management of complex building is characterized by its compactness due to pipe and grid connections. The energy subsystem decisively influences the activity of the subsystem of consumers, although its role is rather to serve them.

The hierarchical feature of the energy subsystem is applied in the preliminary design of the energy management in order to decompose the global task of optimization for the choice of the optimal variant of the energy management structure in complex buildings.

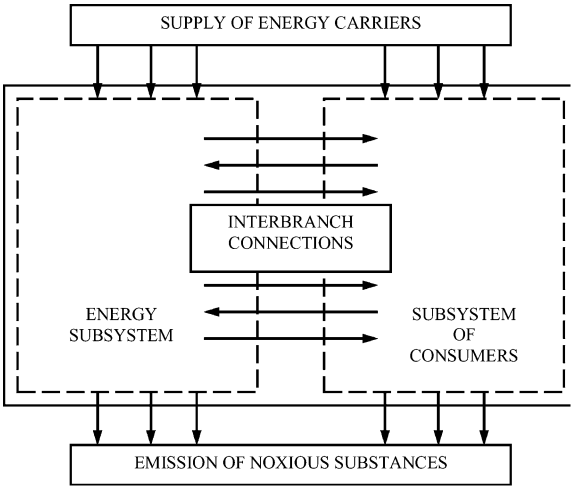


Fig. 4.1 The concept of energy management of complex buildings as “an energy system”

The energy subsystem of complex buildings belongs to open systems exchanging materials, energy, and information with the environment. Connections with the environment are external ones. Among external connections of the energy subsystem of complex buildings the following groups may be distinguished:

- connections between the energy subsystem of complex buildings with the domestic energy system,
- restrictions concerning capital expenditures, the supply of machines, materials, fuels, and energy,
- connections with the natural environment.

External connections are characterized by inertia. This means that additional demands for energy carriers and energy installations and devices cannot be realized at once. Special attention should be paid to connections with the natural environment mostly due to negative ecological results.

Calling a building “an energy subsystem” means that such a structure is treated as a set of installations and devices whose task is to produce, process, transport, and distribute the energy carriers required for the needs of complex buildings, and also a set of connections between these installations of various kinds such as heating, ventilating installations, and air-conditioning, including small-scale CHP units. The connection of CHP units with cooling systems permits the so-called “trigeneration” technology to be realized [2]. Systems applying trigeneration in complex buildings are called building, cooling, heating, and power (BCHP) systems. In such systems, fuel cells may also be used. Such systems utilize natural non-renewable resources much more effectively.

The idea of the energy management of complex buildings as an energy system is presented in Fig. 4.1. In the energy management of complex buildings, characteristic subsystems are to be distinguished, viz., the energy subsystem (responsible

Fig. 4.2 Airport terminal building—Brac Island, Croatia

for the production, processing, transport and distribution of the energy carriers inside the building) and the subsystem of energy consumers.

4.2 Examples of Complex Buildings

4.2.1 Airports

Modern airports consume much energy. In terminal buildings and non-passenger areas, many installations and much energy equipment are used for heating, air-conditioning, dehumidification, cooling, and power generation. Owing to air safety, airports are also equipped with backup power generation systems. Such complex buildings are characterized by high electricity consumption for a huge number of electrical devices. A significant amount of electricity is consumed for air traffic maintenance systems (radars and navigation systems, radio stations, aircraft service, and lighting systems on the runways and on aprons). The energy demand in airports depends on many various structural factors, e.g., thermal insulation of buildings, glazing ratio, infiltration, wall orientation, building height, construction materials, and external cover systems (Fig. 4.2).

In such complex buildings, the energy demand also highly depends on operational factors, such as occupancy time during the day and seasonal fluctuations, number of passengers and workers, area of air-conditioned spaces, heat gains from process equipment, and so on. A huge amount of energy in such buildings is

consumed by facilities usually placed within the airport area, such as luggage stores, shopping centers, restaurants, and so on. The demand for heating and cooling in such facilities is closely related to the geographic situation of the airport and external meteorologic conditions. The simultaneous demand for heating, electricity, and cooling provides an opportunity to apply CHP units instead of traditional heating systems in such complex buildings [6]. CHP units may be connected with the production of cooling agents, particularly in absorption chillers, forming the trigeneration systems.

4.2.2 Hospitals

Hospitals are characterized by unique and high-energy consumption requirements. Such buildings require heating and lighting 24 h a day, and a huge amount of energy for air-conditioning, ventilation, sterilization, compressed air installation, laundries, food preparation, and other equipment. In hospitals heat is delivered to consumers in the form of hot water or steam. Steam is also used in sterilization and humidification systems. Due to the large number of occupants, hospitals are characterized by high hot tap water consumption. Electricity is used in many types of installations and equipment in hospitals. The highest demand for electricity occurs in the following installations: the lighting system, the air-conditioning system, compressors of process air, water-circulating pumps, special medical equipment (diagnosis and treatment devices), and standard office equipment.

Usually, there are two types of compressed air installations in hospitals, viz., technical and medical air. A technical installation does not concern the patients and is used for pneumatic control systems and other technical purposes. Medical compressed air is a high-quality medium, used for the care and treatment of patients. It is supplied in the medical breathing equipment and in medical tools powered by compressed air.

Cold plays an important role in hospitals. In most cases, the cold is transported using installations of ice water. The internal climate (temperature and humidity of ventilation air) must be controlled. Due to strict medical requirements, in some rooms (operating theaters, diagnostic rooms) the internal air parameters have to be controlled very precisely. Large numbers of filters (mechanical, chemical, and biological) lead to high electricity consumption by the air-conditioning system in these rooms. Due to the high cooling demand, in many modern hospitals absorption chillers are used instead of traditional compressor refrigeration systems. Such chillers may be driven, among other things, by waste heat from CHP units based on microturbines or piston engines. More innovative projects in the energy management of hospitals suggest the application of fuel cells.

4.2.3 Office Buildings

Office buildings are considerable energy consumers, mainly of electricity. In Europe, office buildings consume annually 100–1,000 kWh/m^2 [10]. The level of energy consumption depends, of course, on the location of the building, the time of operation during the day and the week, the construction of the building, internal equipment, applied energy installations and devices, the number of occupants, and so on.

The operation of such buildings is connected with a high-energy demand for air-conditioning systems. In many cases, the demands are covered by conventional heating, ventilation, and air-conditioning (HVAC) systems, but in some modern buildings more and more often a concept of distributed environmental indoor climate control systems is realized. These systems supply conditioned air directly to individual office rooms or spaces [3].

Huge amounts of electricity are also consumed by internal office equipment, such as computers, printers, fax machines, copying machines, and so on. Usually, offices are closed at night and during weekends, so that the office equipment is not used at that time. Often the electrical devices are in a standby mode at that time, consuming only a small amount of electricity. It is possible to reduce this electricity consumption in offices by switching off unused devices.

Due to the cyclic demand for energy carriers in office buildings, various accumulative systems of heat and cold may turn out to be profitable. CHP or trigeneration units in such buildings are often equipped with storage tanks for heating or cooling media. The application of storage tanks allows the load to be equalized and makes it possible to operate the heating and cooling installations in a more efficient load range. Such accumulative systems may also be realized in a passive way, e.g., by applying natural "night-cooling" ventilation (Fig. 4.3).

4.2.4 Sports and Recreation Buildings

Sports and recreation buildings (e.g. swimming pools, sports halls, and ice rinks) are structures with unique energy demands.

Swimming pools consume a huge amount of energy for heating the pool water to an adequate temperature. Due to the required high internal temperature, energy consumption for space heating is also significant. This is why heat recovery systems are applied in such structures to save energy. Due to water evaporation from the pool surface a dehumidification system is often applied. The dehumidification system controls the humidity in an indoor swimming pool in order to ensure thermal comfort and avoid condensation on cold surfaces. Released moisture includes some chlorine or bromine disinfectants. Such compounds may be harmful (mainly due to corrosion) to the equipment that remains in contact with them.

Sports halls are characterized by a huge cubature and involve special heating systems. Thermal comfort in sports halls is one of the most important decisive

Fig. 4.3 Modern office building

factors in a heating installation. One of the ways to ensure this comfort is to apply radiant ceiling panels. In this case, the radiant panels are a very energy-effective way to keep the internal temperature at a suitable level. An appropriate air-conditioning system in sports halls is also a real challenge. Very often during sporting events the halls are full of people. Their numbers inside the hall determines the level of air change. In most cases, such structures involve a large-load air-conditioning system, so that its efficiency is crucial to the overall energy balance of such buildings. Sports halls also consume a huge amount of electricity for lighting.

Keeping an ice rink in operation is, of course, connected to a huge energy consumption for cooling. In most cases, compressor refrigeration systems are used. The application of compressor refrigerators facilitates the control of the ice cooling process, but due to electricity used as a driving force it is quite expensive. The demand for heat in the building or in its vicinity permits CHP units with absorption systems (trigeneration technology) to be applied. Good quality ice involves suitable humidity of the internal air (Fig. 4.4).

4.2.5 Shopping Centers

Shopping centers are often large and complex structures. Such complexes may include shops, cinemas, restaurants, laundries, and car parks. Energy requirements for these spaces are quite different. The control of indoor air parameters, the supply of outdoor air, the management of exhaust gases, refrigeration requirements, and

Fig. 4.4 Water park building

heat removal systems are only some of the problems in the energy management of such complex buildings. In most cases, the central heating or central air-conditioning system is insufficient for all spaces. This is a concern for small individual shops, sometimes using individual air-conditioning systems. In most large shopping centers there are also food storage areas, which require reliable cooling media at several temperature levels. This is why such complexes often have their own backup power system. The energy consumption in shopping centers varies during the day and the week, which requires the application of heat and cold storage systems (Fig. 4.5).

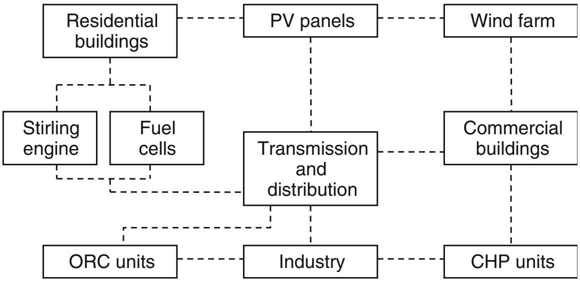
4.3 Modern Distributed Energy Systems in Complex Buildings

Modern complex buildings such as office buildings, hospitals, supermarkets, hotels, and so on demand a rich set of different energy carriers to achieve thermal comfort and cover the process needs. Rising standards of rational energy utilization require the application of new devices and technologies in such buildings. In recent years, new trends in the field of energy production by distributed energy systems in complex buildings have arisen. Distributed energy production, also called decentralized generation or on-site generation, involves energy production by many small energy systems, like small-scale combined heat and power (CHP) units, fuel cells, trigeneration technology, and so on. The concept of this idea is presented in Fig. 4.6.

A typical power generation system needs a central power unit. Usually, this is a large power plant, heating plant or CHP plant, connected to high-voltage grids and

Fig. 4.5 Shopping center

Fig. 4.6 Concept of the distributed power system



heat distribution networks. The operation of such a system generates losses in energy transmission and distribution to consumers. The application of distributed energy systems reduces these losses, because energy carriers are produced close to the consumers, in many cases inside the complex buildings. Such a solution reduces the number and size of distribution networks that must be constructed.

4.3.1 *Small-scale Cogeneration Systems for Application in Buildings*

4.3.1.1 Energy Production in the Cogeneration Process

Heat and electricity are the basic final energy carriers consumed in complex buildings. Therefore, from the economic and ecological points of view their

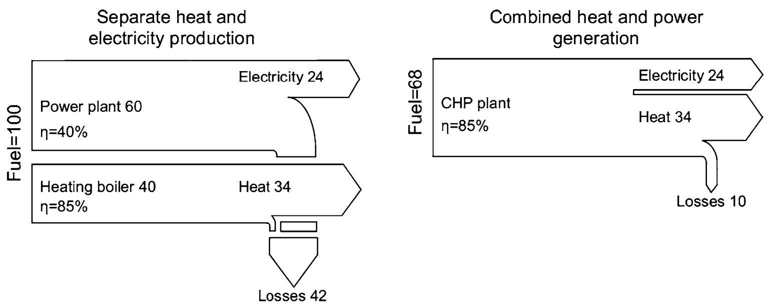


Fig. 4.7 Flow chart comparing separate heat and electricity production with a small-scale CHP plant; η—energy efficiency

production should be realized in an optimal way. Separate production of electricity and heat from fuels is a thermodynamically less effective process. One of the best solutions to be applied in buildings is combined heat and power production (cogeneration). Cogeneration is the simultaneous generation of two different forms of useful energy, using one energy source. The process permits a high overall thermal efficiency to be achieved in comparison with separate energy production. The most common cogeneration process in modern buildings is CHP generation. Although a small-scale cogeneration plant may only have an electrical efficiency of about 30 %, which is less than that of a typical power station, the ability to use waste heat makes it definitely more energy efficient. CHP plants can operate with an energy efficiency of up to 90 % and even higher if they are fed with natural gas. This leads to lower operational costs and lower environmental damages. Figure 4.7 shows the energy effects of the cogeneration process. The left chart in Fig. 4.7 shows the energy input and output in the case of separate heat and electricity production. The right one presents the energy flows in a small-scale cogeneration plant.

In order to apply a small-scale CHP unit efficiently in complex buildings the heat and electricity demand must occur simultaneously during a specified number of hours over the whole year [9]. Meeting this requirement determines whether the investment achieves a positive economic effect. The positive effect results from the replacement of heat and electricity produced in central plants by the local production of these energy carriers in a CHP unit installed inside the complex building.

4.3.1.2 Combined Heat and Power Units Based on Piston Engines

In general, two basic types of piston engines are used for power generation: the spark-ignition engine and the diesel engine. These units can be started up in a very short time; that is, in less than a dozen seconds or so. Spark-ignition engines are environmentally more friendly than diesel engines but less efficient. The energy

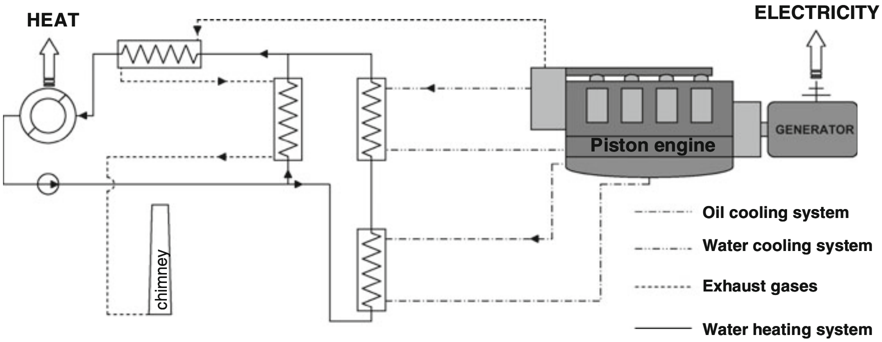


Fig. 4.8 Heat sources in the piston-engine-based CHP unit

efficiency of spark-ignition engines reaches 43 % while diesels can achieve nearly 50 %. The efficiency of diesel engines is rather stable when the load changes. At 50 %, load the efficiency of a spark-ignition gas engine drops by 10–15 %. Because spark-ignition engines may be fed by natural gas they are more popular for power generation today. Power generation units based on piston engines are available in a wide range of sizes, from 1 kW to 50 MW [11].

Piston-engine-based CHP units are the most common small-scale cogeneration plants for application in buildings. CHP units realize a cogeneration process with low investment costs and a relatively high-energy efficiency (even at low load). In such a plant, the piston engine drives the generator where the electricity is produced. Heat is supplied by the cooling system of the engine from several heat sources at different temperatures. In most cases, the heat is recovered from the following heat sources:

- water jacket,
- exhaust gases,
- lubrication system,
- turbosupercharger cooling system.

Most heat is recovered in the water jacket by hot water with a temperature of 80–90 °C. Exhaust gases can provide hot water with a higher temperature, even close to 120 °C. It requires an additional heat exchanger. After the heat exchanger the exhaust gas temperature is about 120 °C. A further reduction of the exhaust gas temperature requires the application of condensing heat exchangers. Such a solution requires additional investment costs for the heat exchanger, but it is justified when the low-temperature heating system (for example the floor heating system) is applied in the building. Usually, heat is supplied to the heating systems by a hot water installation, but in particular cases steam can also be generated (e.g. in hospitals). A flowchart of a CHP unit based on the piston engine is presented in Fig. 4.8. The diagram shows an exemplary configuration of the heat recovery system in the cycle. The estimated energy flow (Sankey diagram) for the typical CHP unit based on a piston engine is presented in Fig. 4.9.

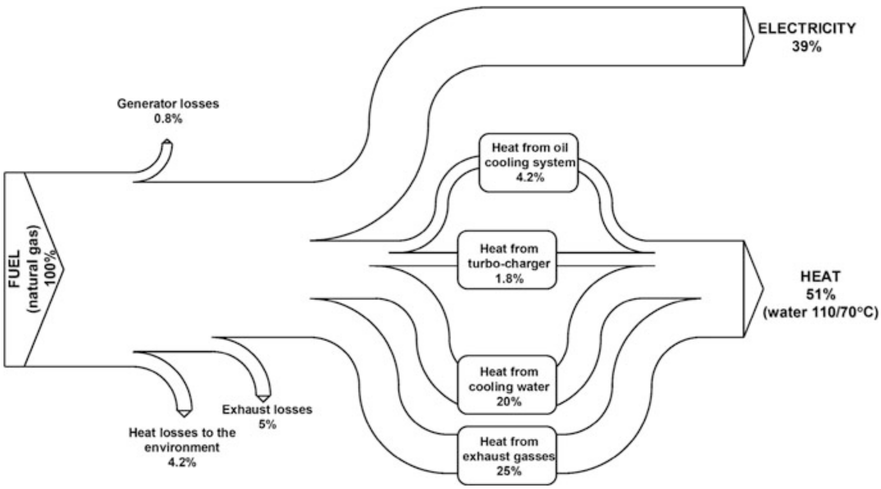


Fig. 4.9 Sankey diagram of energy flow in the CHP unit with a piston engine

The operating speed of the engine depends on the size of the CHP unit. Smaller engines operate at higher speeds; larger ones at a lower speed. Usually, the CHP unit is synchronized with an electricity grid which operates at a frequency of 50 or 60 Hz. This is why the operating speed of the engine must be adjusted to those frequencies. There are three piston engine classes:

- high speed, <3.5 MW, operating at an engine speed of 1,000–3,600 rpm,
- medium speed 1–35 MW, 275–1,000 rpm,
- low speed 2–70 MW, 58–275 rpm.

The engine efficiency and power density (power output in relation to the engine capacity) depend on the speed of the engine. Generally, larger and slower engines operate with a higher efficiency, but the output power in relation to their size is rather low. High-speed engines are less efficient but supply more power output from the capacity unit.

CHP units with piston engines may be fed with the following fuels, among others:

- natural gas,
- LPG,
- biogases;
  - landfill gas,
  - gas from biomass gasification,
  - gas from sewage-treatment plants,
  - gas from biological fermentation,
- waste gases from industrial processes,
- diesel oil,
- liquid biofuels.

Table 4.1 Energy performances of the exemplary commercial piston-engine-based CHP units

	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5
Electric power (kW)	43	100	526	1,063	5,005
Electric efficiency (%)	33.3	34.1	39.5	40.8	41.4
Heat production (kW)	72	167	635	1,190	6,355
CHP ratio	0.6	0.6	0.83	0.89	0.79
Overall efficiency (%)	89.1	90.1	87.1	86.4	94

The operational costs of the CHP unit depend strongly on the type of fuel used. Waste gases, landfill gases, and gases from sewage-treatment plants are usually low-cost fuels. This is why such units are more and more popular in places where waste fuel is available. However, a piston engine is dedicated to a specified range of fuel parameters, and their limits must not be exceeded. Some undesirable substances in the fuel may significantly shorten its lifetime.

At present, there are many kinds and configurations of CHP plants with piston engines available on the market. For application in buildings, the most popular CHP plants are fed with natural gas. Table 4.1 shows the properties of five commercially available CHP units. Piston-engine-based CHP units generate vibrations and noise. This is why in some applications, such as hospitals and hotels, efficient noise insulation is required.

4.3.1.3 Combined Heat and Power Units Based on Microturbines

Another way to produce heat and power in cogeneration for buildings is to apply gas microturbines in CHP units. In contradistinction to piston engines, microturbines generate less vibration and noise. They operate with a higher ratio of power output to the size of the unit. In some power ranges, the CHP unit with a microturbine is ten times lighter than the relevant unit based on a piston engine. There is no cooling system in CHP units with a microturbine. The only heat source is the heat exchanger recovering heat from exhaust gases. The block diagram of such a unit is presented in Fig. 4.10.

Microturbines are widely used to supply energy to complex buildings. Modern microturbines are characterized by their relatively simple construction. Therefore, such units are distinguished by high availability in comparison with piston engines. In most cases, microturbines are two-stage machines with a radial wheel. Presently on the market, two types of microturbines are available: with or without internal heat recovery. In microturbines without internal heat recovery, the air–fuel mixture burns in the combustion chamber, and the hot flux of flue gases expands in the turbine. The turbine drives the electrical generator. Such turbines operate in a simple thermodynamic cycle, and they are cheaper and more reliable than microturbines with internal heat recovery. These latter use a heat exchanger for heat regeneration which heats the inlet air by exhaust gases. The application of such a solution rapidly increases the efficiency of the unit. The energy efficiency of

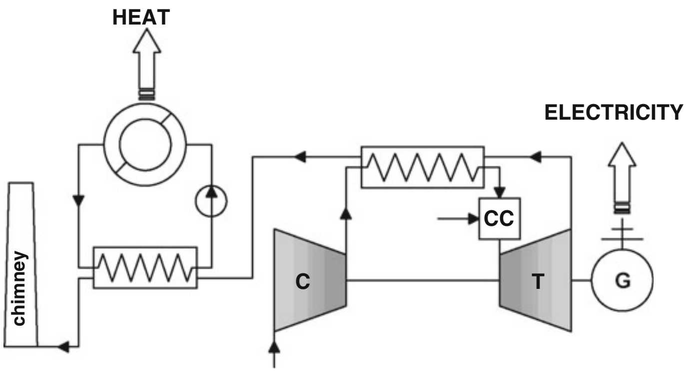


Fig. 4.10 Block diagram of microturbine based CHP unit

Table 4.2 Energy performances of the exemplary commercial microturbine based CHP units

	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5
Electric power (kW)	65	80	100	100	350
Electric efficiency (%)	28.8	25.7	30	27.6	32.1
Heat production (kW)	120	150	155	172	582
CHP ratio	0.54	0.53	0.65	0.58	0.6
Overall efficiency (%)	82	74	77	75	86

modern microturbines used in small-scale CHP units is comparable with the efficiency of much larger gas turbines. Microturbines manufactured today reach about 32 % electrical efficiency. The performance of some commercially available CHP units with microturbines is presented in Table 4.2.

4.3.1.4 Combined Heat and Power Units Based on Stirling Engines

A Stirling engine is an external combustion engine operating by cyclic compression and expansion of the working fluid at different temperatures. In such an engine heat is converted into mechanical work. The heat used to drive the engine is delivered from outside to the cylinders, which are completely sealed. The engine was originally designed by the Scottish inventor Robert Stirling who received his first patent in 1816. The first Stirling engines used air as working gas, but in modern engines hydrogen and helium are also applied. A typical Stirling engine works with two cylinders: a hot (compression) cylinder, and a cold (expansion) cylinder. Such a unit is presented in Fig. 4.11. The cylinders are linked together, and very often a heat regenerator is also applied between them. The heat regenerator increases the thermal efficiency of the Stirling engine compared with a unit without such a heat exchanger.

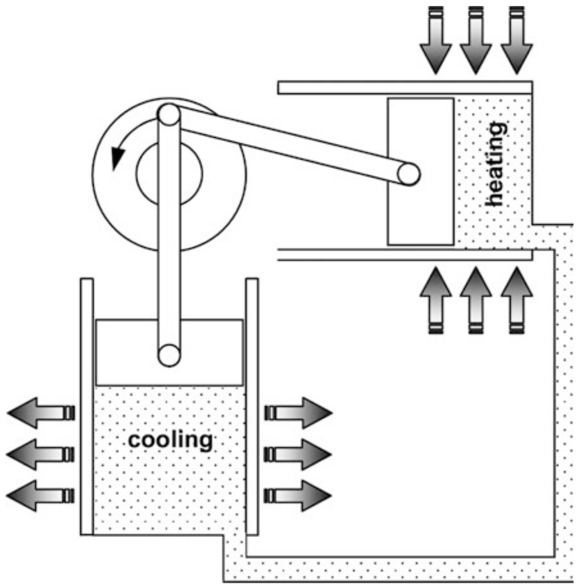


Fig. 4.11 Typical two-cylinder Stirling engine

There are many possible configurations of the Stirling engine. The engines can be distinguished by the way they move the working gas between the compression and expansion spaces. In general, there are three major configurations: alpha, beta, and gamma. The alpha-type Stirling engine has two pistons in separate cylinders. The heat is delivered to the hot cylinder and leaves the engine through the cold one. It is a quite efficient configuration, but there are some material problems due to the relatively high temperature of the working hot cylinder and its seals. A beta-type engine uses two power pistons working in the same cylinder on the same slider. Such a solution solves the technical problems of moving the hot cylinder and its seals. A gamma-type engine is a beta Stirling engine in which the power piston moves in a separate cylinder along the displacer piston cylinder, but it is still connected to the same flywheel. The working gas in the two cylinders can flow between them. Such a solution is mechanically simpler but generates a lower compression ratio. There are many more configurations of Stirling engines (e.g., rotary and free-piston engines), but they are not used in complex buildings.

A great advantage of the application of the Stirling engine is the possibility of using an external heat source. Theoretically, Stirling engines may be driven by any heat source; for example, combustion gases, waste heat or solar energy. Stirling engines work with a rather low efficiency but the possibility of using renewable energy sources makes them a really attractive solution for application in complex buildings. In buildings, waste heat may also be used for heating and the cogeneration technology may be realized.

Even solid fuels may be used to drive a Stirling engine. There are many examples of successful projects with units fed with wood pellets, straw, sawdust, and other types of biomass. The biomass may be burnt directly in the unit or

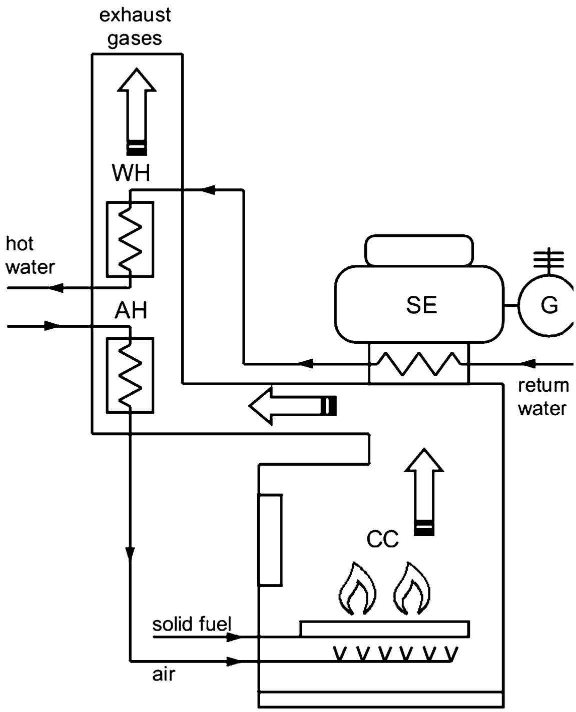


Fig. 4.12 Diagram of CHP unit based on Stirling engine powered by biomass; *CC* combustion chamber, *G* generator, *SE* Stirling engine, *AH* air heater, *WH* water heater [1]

gasified and then used as gaseous fuel in the combustion chamber. Figure 4.12 shows the block diagram of a CHP unit with direct combustion of the biomass.

The size of a typical Stirling engine for buildings ranges from 1 to 200 kW, but in some applications larger units are also used. Nowadays, small natural gas-powered CHP units are more and more popular, used not only in commercial but also in residential buildings. Table 4.3 shows the performance of exemplary CHP units with a Stirling engine powered by renewable energy sources.

4.3.1.5 Combined Heat and Power Units Based on Fuel Cells

Another possibility for cogeneration in complex buildings is the application of fuel cells. A fuel cell is an electrochemical device which directly converts the chemical energy of a fuel into electricity. The production of electricity in the fuel cell results from the reaction between the fuel and an oxidizing agent [8]. The principle of operation of the fuel cell is similar to electrolysis, but vice versa; that is, gases such as hydrogen and oxygen (or air) are pumped in, and DC electricity is the output. The oxidation (combustion) consists in the flow of electrons from the external electronic orbit of the fuel atoms to the external electronic orbit of the oxygen atoms, completing them into electron octets. In a traditional combustion chamber this occurs at a high temperature. If, however, this process is divided in such a way

Table 4.3 Energy performances of exemplary commercial CHP units with a Stirling engine

	Fuel	Working gas	Electrical power (kW_e)	Heat flax (kW_t)	Overall efficiency (%)
Unit 1	Biomass	Helium	75	475	86
Unit 2	Biogas	Hydrogen	43	90	75–80
Unit 3	Wood pellets	Helium	35	140	87
Unit 4	Biogas	Helium	10	26	89

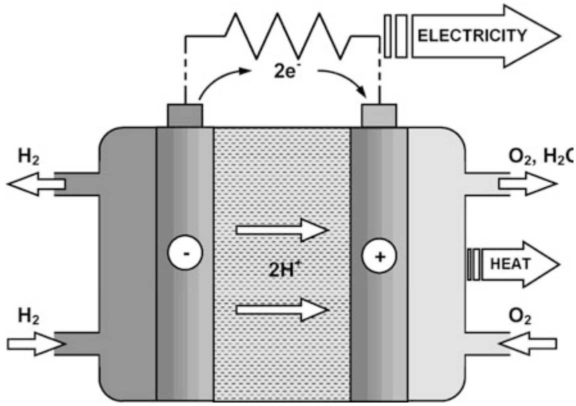


Fig. 4.13 Hydrogen fuel cell

that first on the fuel electrode the fuel atoms emit electrons and these are passed by the electrical circuit to the oxygen electrode, in the external electrical circuit electrical current will flow. In contradistinction to high-temperature combustion in the combustion chamber, the conversion of the chemical energy of fuels to electricity taking place in the fuel cell is often called "cold combustion". Thus, this conversion takes place without combustion, and its products are electricity, heat and water. There are few or no harmful emissions. The idea of a hydrogen fuel cell is presented in Fig. 4.13. This technology was developed in the nineteenth century, but the first commercial applications were introduced in the 1990s.

At present, there is a wide variety of fuel cell types, each using different fuels, electrodes, electrolytes, and so on. Fuel cells may be classified by the type of electrolyte which is used: alkaline fuel cell (AFC), proton exchange membrane fuel cell (PEMFC), phosphoric acid fuel cell (PAFC), molten carbonate fuel cell (MCFC), and solid-oxide fuel cell (SOFC). A summary of the main fuel cell types and their characteristics is presented in Table 4.4.

Today, fuel cells are not yet produced on a large scale, but some of their positive features may lead to their application in complex buildings in the near future. At present, there are only a few fuel cell producers who offer commercial units applicable in complex buildings. Nevertheless, interest in this technology is continually rising, which is confirmed by a significant number of new demonstration

Table 4.4 Classification of fuel cell types and their characteristics

Fuel cell type	Power range (kW)	Working temperature (°C)	Electrolyte	Reforming	Electrical efficiency (%)	Overall efficiency (CHP) (%)
ACF	<100	60–100	Aqueous potassium hydroxide (KOH)	–	60–65	–
PEMFC	<250	60–120	Sulphonated organic polymer	External	35–46	60
PAFC	<1,000 (most often about 200)	150–220	Phosphoric acid	External	35–44	80
MCFC	<2,000 (most often about 250)	600–700	Li_2CO_3/K_2CO_3	External/ internal	45–56	85
SOFC	<3,000 (most often about 200)	700–1,000	Y_2O_3/ZrO_2	External/ internal	44–55	85

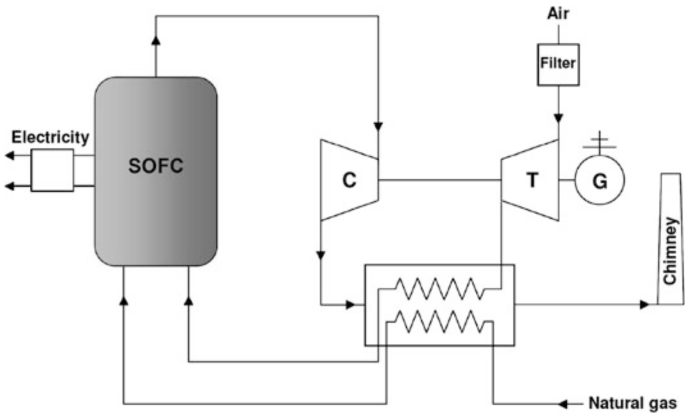


Fig. 4.14 Hybrid cycle of fuel cell and gas microturbine

projects with fuel cells in CHP units. Many of them are installed in commercial buildings.

Heat generated during the process in the fuel cell may be successfully used in a CHP unit, just as heat from piston engines or a microturbine may be used. The advantages of CHP units with fuel cells are a small number of moving parts, silent operation without vibrations, and higher electrical efficiency (by about 10 %) in comparison with CHP units with a traditional piston engine or a microturbine. The output load in such CHP units may be easily changed within a wide range. CHP units with fuel cells can operate continuously for a long time without breaks for repairs.

Besides the traditional application of fuel cells in cogeneration plants producing heat and electricity, the newest concepts propose the application of fuel cells in hybrid units together with gas microturbines [12]. At present, such units are not available on a large commercial scale due to their complicated construction, but their high-energy performance may change this in near future. The electrical efficiency of such hybrid units reaches 70 % in small units and nearly 75 % in larger ones. In most cases, hybrid units use the SOFC type. This type of hybrid unit is presented in Fig. 4.14.

4.3.1.6 Trigeneration Technology for Complex Buildings

Modern complex buildings are characterized by a composite structure of energy management resulting from the generally growing application of various kinds of installations for heating, ventilation, and air-conditioning. Many buildings require electricity heating and cooling, simultaneously. That provides opportunities to use waste heat for cooling and the application of trigeneration systems [4, 11]. The term “trigeneration” means an integrated CHP unit with a cooling aggregate. This integration allows generation of heat, electricity, and a cooling agent in one

system. As a heat source the heat from a piston engine, microturbine or, for example, a fuel cell can be used. Especially, in out-of-heating seasons those sources dispose large amounts of waste heat. Waste heat may be successfully used for the production of cooling agents, which is necessary for air-conditioning or other cooling systems (e.g., food storage and air dehumidification). The application of trigeneration systems in buildings is called building, cooling, heating, and power (BCHP) technology. Such solutions in buildings utilize input energy in a very efficient way and are becoming more and more interesting [15].

One of the most efficient ways to utilize waste heat for cooling is to apply absorption cooling devices. Absorption chillers, in contradistinction to compressor refrigerators, do not require much mechanical energy. These devices are characterized by high durability, high reliability, low vibration, and low noise emission. Therefore, absorption chillers are nowadays the most popular units for BCHP applications.

Usually, absorption chillers in BCHP systems are powered with hot water or steam, or directly with hot exhaust gases. At present, the two most popular types of absorption chillers on the market are lithium-bromide and ammonia chillers. In most cases for BCHP systems in buildings (cooling, air-conditioning and so on), lithium-bromide machines are used. The absorbent in this kind of device is environmentally friendly lithium-bromide ($LiBr + H_2O$), and the working fluid is water. In buildings where a lower temperature is required ammonia absorption chillers are applied. In such machines, the ammonia solution ($H_2O + NH_3$) is used as a working fluid. It allows to decrease the temperature of the cooling agent to below 0 °C. Such devices, in comparison with lithium-bromide chillers, are more complicated and more expensive.

Due to the toxicity of ammonia they require special construction solutions and extra technical maintenance to ensure operational safety. In presently offered single-stage absorption chillers the coefficient of performance (COP) reaches a level of 0.8. In the case of double-stage machines, this coefficient is much higher and reaches a value of 1.5. Triple-stage chillers do not yet reach a satisfactory technical level, and they are not commercially used on a wide scale in complex buildings. Basic energy characteristics of single- and double-stage absorption chillers have been gathered in Table 4.5.

A block diagram of the typical BCHP system for heat, power, and cooling production is presented in Fig. 4.15. In this system, a piston engine and absorption chiller have been applied. Additionally, in order to cover the peak heating demand a peak boiler and storage tank have been used. When the heat consumption is lower than its production in the BCHP unit, the heat accumulates in the storage tank of hot water. When the demand for heat is larger, the heat storage tank provides heat to consumers. In periods of increased heat demand the peak boiler connected with the BCHP unit is switched on and produces additional heat.

It is also possible to integrate both absorption and compressor chillers in the BCHP system. Such a solution is presented in Fig. 4.16.

Table 4.5 Energy parameters of single- and double-stage commercially available absorption chillers

	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5
Cycle type	1-Stage	1-Stage	1-Stage	2-Stages	2-Stages
Heat source	Hot water 90–130 °C steam	Hot water 95 °C	Hot water 90–130 °C steam	Hot water 180 °C steam	Hot water 180 °C steam
Cooling power (kW)	394	1,055	2,008	1,266	2,318
Coefficient of performance	0.63	0.7	0.71	1.20	1.21
Electricity consumption (kW)	3.8	4.05	9.7	10.6	20.5

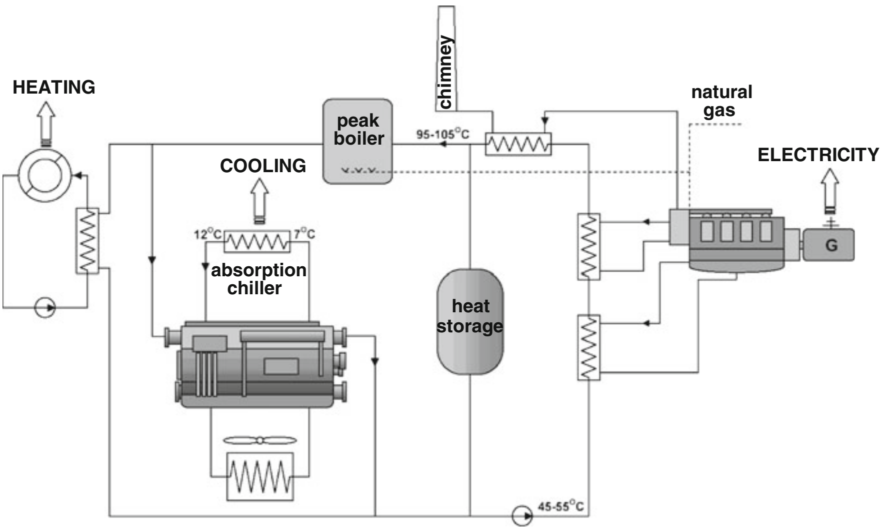


Fig. 4.15 Block diagram of the typical BCHP system with application of the absorption chiller

4.4 Utilization of Renewable Energy Resources in Complex Buildings

Renewable energy is defined as energy which comes from the natural environment and is constantly or repetitively replenished. Nowadays, there are many possibilities for generating energy by applying renewable energy resources. Most renewable energy systems (plants) are set up for the production of some particular energy carriers and their sale to the distribution network (e.g., electricity from a

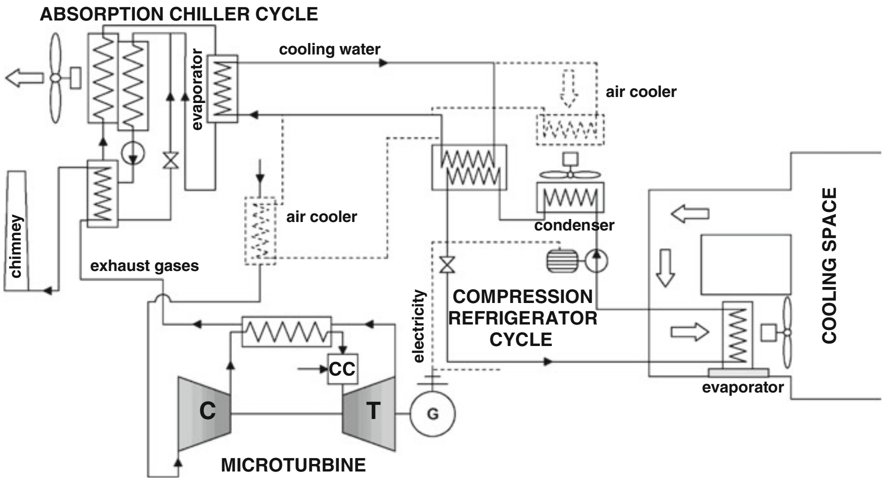


Fig. 4.16 Block diagram of the BCHP system integrated with both absorption and compressor chillers applied in complex buildings [14]

hydro-power plant). Therefore, there is also a large potential for renewable energy to be used in the vicinity of complex buildings.

4.4.1 Solar Energy

4.4.1.1 Active Solar Heating: Solar Collectors

One of the most efficient ways to utilize solar energy in buildings is to apply solar collectors for space heating and the production of hot tap water. Such a process may be realized by many different types of solar collectors. Solar collectors have often been applied in single house-heating systems, but nowadays they are also more and more popular in complex buildings. They may be mounted vertically on the wall of the building or on its roof. Figure 4.17 presents roof-placed solar collectors.

Flat-plate water solar collectors. These collectors consist of an absorber plate, a glazing cover (sometimes a plastic cover), casing, and insulation (Fig. 4.18). The absorber plate should be painted black to absorb most of the solar radiation. A good quality glazing is very important. In most cases, there is only one layer of glass, but more efficient solar collectors sometimes have two glazing layers. Due to the internal greenhouse effect only a small amount of the heat captured by the absorber escapes the solar collector.

Evacuated tube collectors. Collectors of this type are made up of rows of parallel tubes in which the working fluid circulates. There are several kinds of

Fig. 4.17 Roof-placed solar collector

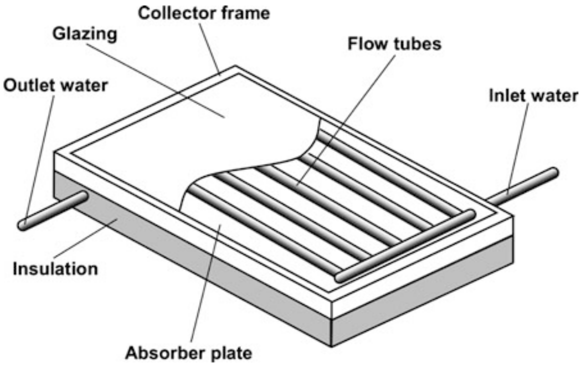


Fig. 4.18 Flat-plate water solar collector

evacuated tube collectors. The most effective solution is heat pipes with special low-vaporizing fluid. The pressure value of the fluid is chosen to guarantee evaporation at the hot part and condensation at the cold part. Such a solution provides a very efficient heat transfer, but is relatively expensive. The concept of evacuated tube collectors is presented in Fig. 4.19.

Flat-plate air solar collectors. In these collectors (Fig. 4.20) air is used instead of water as a working fluid. Air collectors are generally less efficient than water collectors, but their construction is simpler and less expensive. They are often applied for space air heating and drying systems.

Unglazed solar collectors. These are not as efficient as glazed collectors but are a cheaper solution often applied in water heating systems of swimming pools. The temperature of water in swimming pools is relatively low in comparison to a space heating system or the preparation of hot tap water, so that the efficiency of these collectors is less important.

Solar concentrators. These systems use mirrored surfaces concentrating solar radiation. They are not commonly applied in building heating systems. They are used rather as a heat source to drive heat engines for electricity production. Some demonstration applications with a steam turbine and with Stirling engines exist.

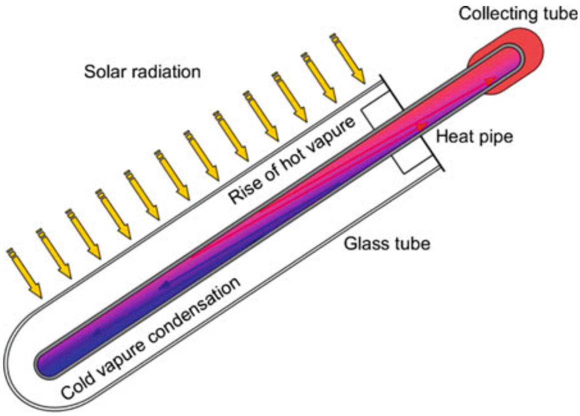


Fig. 4.19 Evacuated tube collectors with heat pipe technology

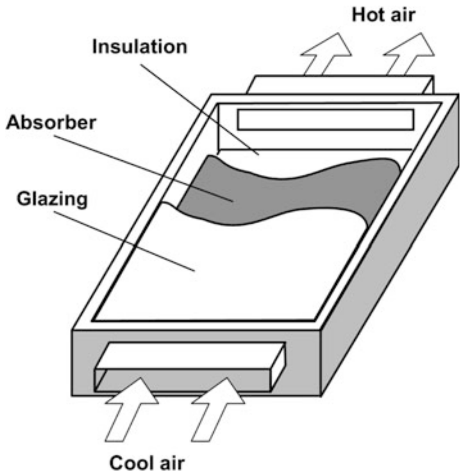


Fig. 4.20 Flat-plate air solar collectors

The advantage of these systems is the possibility to heat the working fluid to a high temperature. Such systems are quite expensive because there are only a few manufacturers in the world producing solar concentrators. The best effects are achieved when the mirrors track the sun using a special mechanical system which rotates the concentrators in two axes (both horizontally and vertically). As distinct from flat-plate collectors, the solar concentrators can only focus direct sunlight, and therefore they do not act well in cloudy weather. There are two types of concentrators: line-focus and point-focus ones.

Solar radiation varies during the day, strongly depending on weather conditions. The heating demand also changes at the same time. Accordingly, the application of thermal storages for such systems may be very useful. In most cases, thermal storage is realized using tanks with hot water, but there are also solutions with ground thermal storage systems. In huge heating systems it is possible to realize

interseasonal thermal storage, but this requires large well-isolated storage tanks, and in most cases such solutions are not useful.

4.4.1.2 Passive Solar Heating and Day Lighting

Besides directly using solar energy in solar collectors, buildings with appropriate design may also use passive solar techniques. Such techniques may be used to increase significantly the performance of heating, cooling, lighting, ventilation, and dehumidification systems. In some cases, passive solutions may completely displace conventional systems. There are some basic features which should allow a building to use passive solar heating in the best way:

- a large area of glazing surfaces to gain heat from solar radiation,
- well-controlled and efficient heating systems with a load which is adjustable to the quantity of passive solar heat gains in the building,
- orientation of the building rather southwards to capture as much solar radiation as possible,
- massive partitions in the building, which absorb sun radiation during the day and heat the internal air during the night very well; a massive construction of the building prevents overheating in summer,
- good insulation to reduce heat losses,
- location of the building away from shading by other buildings and trees.

Electricity consumption for lighting in complex buildings is significant. For example, in most office buildings the lighting is continuously switched on during all working hours (even in sunny weather) and consumes about 30 % of the electricity delivered to the building. By applying appropriate design solutions in buildings, it is possible to achieve high-energy savings for lighting. Of crucial importance is that the design solutions should consider both daytime lighting and passive heating simultaneously. Good daytime lighting conditions lead to high heat gains, which may be very inconvenient during the summer season. Typical daytime lighting techniques are:

- roof windows and glazed roofs,
- appropriate design so that most rooms are penetrated by daylight,
- light wells inside the building,
- tall glazing on the facade of the building which allows the interior of the building to be lit up.

4.4.1.3 Solar Photovoltaics

Photovoltaic (PV) cells produce electricity directly from solar radiation without any mechanical devices. The PV panels (Fig. 4.21) are silent, easy to handle, and easy to arrange in a building. PV systems may by mounted on roofs and walls of complex

Fig. 4.21 PV panels located on the roof of an office building

buildings, partially substituting some traditional covering materials. Complex buildings are occupied in most cases during the day when the solar radiation may be used for electricity production, so there is no special need for energy storage. The best solution for complex buildings is PV systems working in the on-grid mode, where the surplus of electricity is sold to the domestic power system.

The overall effectiveness of the PV system in complex buildings depends on:

- geographical location of the building and local meteorological conditions,
- location of the PV panels on the building (azimuth and elevation) and application of the sun tracking system,
- area of the PV panels,
- energy efficiency of the PV panels,
- energy efficiency of auxiliary electrical devices (e.g., efficiency of the DC/AC inverter).

A very interesting solution is the combination of PV panels with shading devices, so-called "shadovoltaic" or "photovoltaic solar shades". In this case, the solar shading elements (movable or fixed) are covered by PV panels. Accordingly, such systems may efficiently reduce the solar heat gains and produce additionally electricity.

4.4.2 Wind Energy

Complex buildings, especially office buildings, are often very high structures. This feature permits the use of wind energy. Electricity may be generated in small wind

Fig. 4.22 Micro wind turbines (www.preVent-germany.com)

turbines (microturbines). Such devices are commercially available, and there are two main kinds: with a vertical axis, and with a horizontal one. These compact turbines are often mounted on the top of a building, but there are some disadvantages of such a solution. During their operation micro wind turbines vibrate, and the vibrations are transmitted to the building structure, which may be perceptible by the occupants as an unpleasant noise. Moreover, in nearby buildings turbulences are generated which deteriorate the working conditions of the wind turbines. Tall towers for rotors of the wind turbines allow this problem to be partially minimized, but such constructions are quite massive (for safety reasons) and expensive. Figure 4.22 shows examples of rooftop wind turbine supplying energy to building.

4.4.3 Ground-source Heat Pumps in Complex Buildings

Heat pumps are devices which transfer heat from one space with a lower temperature to another space with a higher one. Of course, this process is possible thanks to input energy. In the case of compressive heat pumps mechanical work is applied. In buildings heat pumps may be used both for heating and cooling. The low temperature heat source is in most cases the ground, from which the heat is transferred using vertical (Fig. 4.23) or horizontal heat exchangers. The heat is

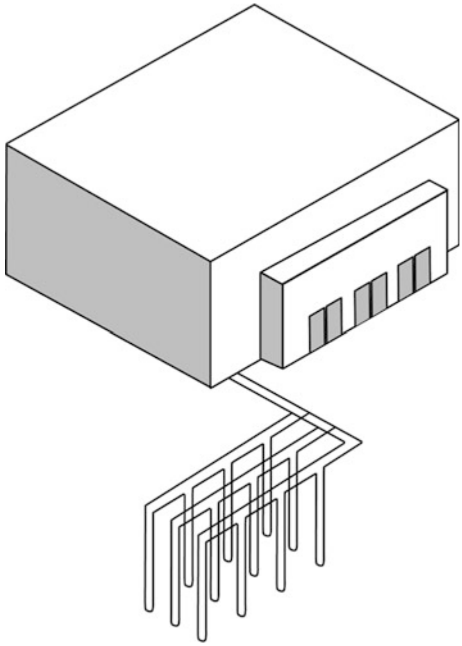


Fig. 4.23 Ground heat pump for a commercial building with a vertical heat exchanger

delivered to the exchanger of the heating system. The application of heat pumps may significantly increase the effectiveness of cooling systems with absorption chillers. There are also internal applications of heat pumps for appropriate heat management in buildings. In such systems, waste heat from cooling zones in a building is used for heating in other zones. Such a solution increases the efficiency of cooling and heating systems and leads to significant energy savings in a building. In general, from the operational point of view, the heat pumps in complex buildings may be divided into the following categories:

- heat pumps working only in the heating mode, providing space heating and/or water heating,
- reversible heat pumps working in the heating and cooling mode, providing both space heating and cooling (air-to-air heat pumps or with a water loop),
- heat pump systems integrated with exhaust-air heat recovery,
- heat pumps with water heaters, fully dedicated to water heating.

In complex buildings, the peak load is covered by a traditional heating system, using a peak water boiler powered by heating oil or natural gas. Of course, heat pumps can be integrated with other heating or cooling systems. For example, the heat pump may work in one system with a cogeneration or trigeneration unit in the building.

4.4.4 Bioenergy for Complex Buildings

Bioenergy is a kind of renewable energy contained in substances supplied from the natural biological environment, which may be used directly in energy devices (e.g., boilers). It is called biomass. From biomass it is possible to produce many kinds of biofuels (e.g., biogas). The chemical energy accumulated in biomass arises mainly thanks to solar radiation. This is why bioenergy may be considered to be solar energy accumulated in organic substances.

4.4.4.1 Direct Biomass Combustion and Biomass Gasification

There are many kinds of biomass which may be utilized in complex buildings, the most popular ones being:

- raw wood, derived from the processing of wood or forestry activities (e.g., sawdust, wood chips and wood pellets),
- energy crops (e.g., willow and poplar),
- wastes from agricultural cultivations (e.g. straw),
- wastes from the food industry and consumer food wastes,
- by-products from the wood industry.

Biomass is mainly used for heat production in complex buildings, but there are some innovative projects for electricity generation, too. A serious problem in buildings is the lack of place for storing the biomass and the wastes from combustion processes. Complex buildings are often located in urban areas. Therefore, the transport of the biomass is also difficult. Direct biomass combustion in such places may turn out to be difficult or even impossible due to emissions to the atmosphere. An example of a better technology for building application is biomass gasification. This process transforms the biomass into fuel where synthesis gas is produced, which is much cleaner than direct combustion in the boiler. Biomass gasification increases the possibilities of applying cogeneration plants in complex buildings. Such units (CHPs based on piston engines, Stirling engines, or even microturbines) very efficiently utilize the chemical energy of the biomass and emit less noxious substances to the environment. Some demonstration projects exist that apply direct biomass combustion in cogeneration or trigeneration technology in complex buildings. For this purpose, Stirling-engine-based CHP units are most promising. Similarly, some demonstration installations of direct biomass combustion in buildings use Organic Rankine Cycles.

4.4.4.2 Biofuels

Biofuels are fuels gained by the conversion of biomass and biowastes. Nowadays, there are many kinds of biofuels, which depend on the biomaterials from which

they are derived and the type of production process in which they are used. There are some possibilities for utilizing biofuels in complex buildings, where the biofuels may feed the heating boilers as well as the cogeneration and trigeneration plants. Such devices must be specially adapted for biofuel combustion (in most cases producing less chemical energy and higher emissions if compared with conventional fuels) or even designed for such fuels. A simpler way to use biofuels is in a co-firing process with conventional fuels. In complex buildings the following biofuels may be used:

- bioalcohols,
- biodiesel,
- green diesel,
- vegetable oil,
- bioethers,
- biogas,
- syngas.

The potential to utilize biofuels in complex buildings is rather limited. The main problems encountered are:

- complex buildings are often located in urban areas; some biofuels (e.g. biogas) are produced in very complex installations, which should not be located near those buildings,
- transport of biofuels in urban areas is quite complicated.

Besides gas and liquid biofuels, solid ones are also produced. However, the limited availability of such fuels and difficulties connected with their combustion in complex buildings restrict the application of these biofuels.

4.5 Supply of Energy Carriers to Complex Buildings

4.5.1 District Heating Supply Systems

In the case of district heating, heat is supplied to a complex building by a heating medium via a heat exchanger center, which transfers the heat from the external heating network to the heating installation of the building. The heating medium is a substance transporting the heat from the CHP or heating plant to the receiver through the heat distribution network. In the building, both liquid and gas heating media may be applied. Each heating medium should comply with the following requirements:

- high thermal capacity,
- low flow resistance,
- low cost,
- low toxicity,
- boiling point parameters.

Owing to these requirements the most popular heating media are water, steam and air.

Water is an easily available heating medium, but in most cases it is contaminated by some organic and chemical substances. This is why, before its use in the heating network the water should be conditioned in a water treatment system. An inconvenience connected with the application of water as a heating medium is its boiling and freezing temperatures. In order to prevent boiling a suitable pressure in the heating network should be kept up. In winter, the water heating network should be protected against freezing. Because of chemical contaminations the other main problematic features of the water heating medium are the following ones: the possibility of gas precipitation from water (air lock of the heating network), boiler scale formation inside the heating installations, and pH reaction responsible for corrosion of the installations. There are also special liquid heating media (e.g., mineral oils and glycol), but their application in heating systems of complex buildings is rather limited.

In some heating networks (especially in industrial systems) steam is used as a heating medium. Such systems have a similar structure as water systems, but due to the properties of steam they are more complicated to maintain. They also work in closed loop cycles like water systems. In the heat exchanger of the consumer the steam condenses to water. The water condensate is collected and pumped to the heating source (CHP or heating plant).

The main problems in the maintenance of steam systems are:

- limited possibilities for heat transport at long distances,
- relatively high temperature of the steam compared with water,
- necessity of removing the condensate from the pipes.

Steam heating systems are not commonly used in complex buildings. Sometimes such applications occur in buildings in the neighborhood of industrial plants, where heating steam is available.

In special locations, air may be applied as a heating medium in a building. For example, the heating air may be delivered to the building from nearby industrial installations. Due to a low heat capacity, a high density with the rise in temperature, and the possible formation of fog, the use of air as a heating medium is expedient only to connect the functions of heating and ventilation in the building.

4.5.2 Electricity Supply

Complex buildings are connected to the high voltage power network and use transformers to reduce the voltage to the appropriate value for the equipment inside the buildings. These transformers and other electrical equipment may be placed inside or outside buildings, usually near the main power grid terminal. They are the most important electrical devices in the whole power system of buildings.

In complex buildings several different types of transformer constructions are used:

- *Ventilated dry-type transformers.* The generated heat is removed by the ventilation air. Such units need enough space to ensure an appropriate air circulation. This type of transformer should be located inside a restricted area for safety reasons and to prevent mechanical damages. Such a transformer is very popular in complex building applications.
- *Sealed dry-type transformers.* The construction of these transformers is very similar to that of dry-type transformers, but they have an additional tank with dielectric gas (e.g. nitrogen) to protect the windings. Such transformers can be installed outside or inside the building. They are often applied in toxic or corrosive environments. They are very reliable devices and require minimum maintenance.
- *Cast-coil transformers.* These consist of windings encapsulated in reinforced resin. Such solutions protect the windings against contaminants and moisture.
- *Unventilated dry-type transformers.* The construction of these transformers is similar to that of ventilated transformers, but all electrical parts are enclosed. The tight case permits such transformers to be applied in unfriendly conditions (contaminated, wet or toxic).
- *Oil-filled transformers.* The windings of these transformers are closed in a tank filled with insulating oil. The oil helps to control the temperature inside the transformer and prevents overheating during high power applications. Such transformers can operate for long periods of time and are very safe.

4.5.3 Water Supply

Water supply systems get water mainly from groundwater sources and surface water locations (e.g., rivers) and supply it to buildings. The water is then, in most cases, purified, disinfected by chlorination and sometimes fluoridated. Then, the treated water either flows by gravity or is pumped to reservoirs. After that it is delivered to consumers. Once the water is used, wastewater is typically discharged to a sewer system and treated in a wastewater treatment plant before being discharged into a river, lake or the sea, as well as for irrigation or industrial use. Typical water supply system consists of the following elements:

- Raw water source located below or above the ground, as underground aquifer, a river or a lake. The raw water is transported to the water treatment system.
- Water treatment system. The raw water is prepared for drinking purposes.
- Drinking water reservoirs with necessary facilities (e.g. water pressure towers, pumping stations, etc.).
- Drinking water distribution network system which delivers the water to the consumers.

Drinking water contains microbiological and physicochemical contamination. There are many parameters of water quality. In public water supply systems, water should at least be disinfected—most commonly by chlorination or the use of ultraviolet light, or it may need some other additional treatment, especially in the case of surface water.

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